United States
Department of
Agriculture

Forest
Service

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Management**

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EVALUATION OF THREE SURVEY METHODS FOR DETERMINING SPRUCE-FIR MORTALITY CAUSED BY EASTERN SPRUCE BUDWORM

Report No. 85-2

3400
March 1985

EVALUATION OF THREE SURVEY METHODS FOR DETERMINING SPRUCE-FIR MORTALITY CAUSED BY EASTERN SPRUCE BUDWORM

by

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ABSTRACT

Precision and cost effectiveness of three procedures for estimating volume loss caused by eastern spruce budworm in spruce-fir stands were compared. The three procedures include: (1) ground sampling; (2) aerial sketch mapping and ground sampling; and (3) aerial sketch mapping and large-scale aerial photography combined with ground sampling.

Three related concerns were also addressed during the project: (1) Could aerial photo stand volume tables be utilized in lieu of ground survey? (2) Was there an advantage in using one film type over another (color infrared or true color)? and (3) Could residual stand volume and basal area be ascertained by any of the three techniques?

Each survey method was capable of estimating spruce-fir volume losses caused by spruce budworm. The two procedures using aerial classification can also be used to determine the location of tree mortality.

Comparing all techniques for cost and precision, the one employing aerial sketch mapping and ground sampling gave the best estimate of volume loss at the lowest cost per acre.

INTRODUCTION

The eastern spruce budworm, Choristoneura fumiferana (Clemens), is a major defoliator of white spruce, Picea glauca (Moench) Voss, balsam fir, Abies

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balsamea, (L.), Mill, and black spruce, P. mariana (Mill), B.S.P. in the lake states. Repeated loss of new shoot growth on host trees results in mortality. Balsam fir of merchantable size (5 in. DBH and over) generally start dying after 5 years of severe (75 to 100 percent) defoliation (Belyea 1952; Blais 1958; Batzer 1973). White spruce begin dying after 6 to 7 years of severe defoliation. If spruce budworm populations are extremely high, heavy feeding results in the destruction of some old foliage in addition to the new growth, and tree mortality is accelerated (Blais 1981).

An outbreak of spruce budworm developed on the Nicolet National Forest in northeastern Wisconsin in 1973 when Erickson (1973) first reported 600 acres of defoliation in 1973. Defoliation was severe on balsam fir and white spruce from 1977 through 1980 in the northern portion of the Forest. During the 1980 outbreak, insect populations on the Nicolet were extremely high. Most of the resulting mortality occurred in balsam fir and white spruce stands aged 39 years or older and covering 12 acres or more. Budworm populations continued to increase on the Nicolet until peaking in 1980; they declined significantly in 1981 and virtually collapsed due to natural causes in 1982(Fowler 1971; Anderson 1975; Munson and Robbins 1979; Munson and Haynes 1981).

Pest management specialists need efficient and cost effective methods to inventory pest caused losses such as those caused by spruce budworm. This information can be evaluated by forest managers and other resource specialists to determine alternative management actions for dealing with these losses. Such data are needed by land managers for setting harvesting priorities, evaluating direct control options, and for land management planning. This paper compares alternative methods for acquiring data on losses caused by spruce budworm.

METHODS

The Nicolet National Forest in northeastern Wisconsin was selected to evaluate three survey methods designed to estimate volumes of spruce-fir mortality caused by the spruce budworm from 1977 to 1982. Forest inventory data indicated that balsam fir and white spruce stands (origin of 1944 or earlier) occurred on 27,918 acres. White spruce stands accounted for 34 percent of this acreage. Two-thirds (66 percent) of the spruce-fir acreage was found on the Eagle River and Florence Ranger Districts. Many of the balsam fir stands were intermixed with other tree species including white spruce, black spruce, quaking aspen, Populous tremuloides Michx.; paper birch, Betula papyrifera Marsh; red maple, Acer rubrum L.; and northern white cedar, Thuja occidentalis L. White spruce stands were primarily plantations composed of 90 percent or more white spruce.

Actual operational use of the three survey strategies are described as follows: Techniques 1 and 2 are briefly described since they are already reported in the literature. Technique 3 is covered in more detail since significant changes were made in adapting it to our specific objective.

SURVEY TECHNIQUE 1 - A GROUND SURVEY

The sampling scheme used for this technique is an adaptation of a three-stage cluster sampling technique (Mog and Witter 1979; Mog, Lynch and Witter 1982; Schumacher and Chapman 1954; Sukhatme and Sukhatme 1970; Yamame 1967). Only two concentric circular plots for tree mortality and tree size measurements were used. The third plot, used to estimate budworm defoliation on small trees, was of no value in this survey. The three levels of information were; forest compartments, spruce-fir stands, and two concentric circular plots. The stands were selected at random. The Forest compartment was not a selection criteria; however, each compartment was represented in the list of selected stands.

Spruce-fir stands on the Nicolet were outlined on a 0.5-inch/mile scale forest map. Stands selected for ground sampling were picked at random using a random number generator on a Texas Instruments (TI-59)[3/] calculator. Thirty-one stands were selected and located on the following Ranger Districts: eleven on the Eagle River Ranger District; eleven on the Florence Ranger District; seven on the Laona Ranger District; and two on the Lakewood Ranger District.

A sampling unit within a stand consisted of two concentric circular plots of 0.05 and 0.20 acre established around a single fixed point. Data on three variables were recorded in the concentric circular plots: (1) tree species; (2) tree mortality; and (3) tree DBH. Tree heights were recorded only in the smaller 0.05 acre plots.

All spruce or fir species five inches DBH or larger were measured. Total tree height for all live spruce and fir trees was measured to the nearest foot using a Suunto clinometer. If the top was broken out, the total height of the remaining portion of the tree was recorded.

The two concentric circular plots made up the composite ground sampling unit. Three composite ground sampling units were located within each spruce-fir stand. Each ground sampling unit was predetermined using national forest compartment and stand maps with compass and distance measurements plotted to ensure complete coverage of the stand. A total of 93 ground sampling units were measured on the Nicolet National Forest.

Dead tree volume (V) was determined by using the equation $V = 0.42\,BH$, when B = basal area of the tree and H = total tree height (Gevorkiantz and Olsen 1955). The tree heights entered into the equation were obtained from height curves drawn by plotting tree height vs DBH, by 1-inch diameter classes, for every tree measured on the 0.05 acre plots. Additional white spruce and black spruce from the 0.20 acre plots were included to increase the data base for both species. The total dead volume parameter was an accumulation of all dead tree volume that died 5 years before and/or during 1983. Trees killed by non-budworm causes such as inundation, fire, etc., were not tallied.

[3/] Mention of commercial products is for convenience only and does not imply endorsement by USDA Forest Service.

SURVEY TECHNIQUE 2 - AERIAL SKETCH MAPPING AND GROUND SAMPLING

This technique employed standard sketch mapping procedures (Anonymous 1970; Klein, et al. 1983) and a ground technique adapted from Lund (1978) by Ford (1984). This adaptation was required because Lund's technique did not deal specifically with tree mortality. Ford substituted tree mortality strata for vegetation strata as presented in Lund's approach.

AERIAL SKETCH MAPPING PROCEDURES - The Nicolet National Forest was color coded on 0.5 inch/mile maps to identify spruce and fir stands. Tree mortality was recorded on these maps by outlining affected stands and classifying the degree of tree mortality due to spruce budworm feeding into strata where:

S = Severe, 50 percent or more of the spruce and fir trees in a stand were killed.

M = Moderate, 20 to 49 percent were killed.

F = Few, 1 to 19 percent were killed.

N = No visible mortality. This last stratum was not sampled because it was not impacted by budworm feeding as expressed by tree mortality.

Spruce and fir trees killed by fire, inundation, blowdown, and other non-budworm causes were not tallied. The smallest area classified was 12 acres because of the difficulty in sketch mapping a smaller area.

Mortality levels were stratified because previous surveys indicated variances differed according to the proportion of dead trees in stands. In addition, the various degrees of mortality were relatively easy to determine during the flights, and forest managers were expected to manage heavily damaged stands differently than those stands with less damage.

Following the aerial survey, stands with mortality were numbered consecutively within strata, and the area was estimated using a computer-generated grid of Nicolet National Forest stand acreages.

GROUND VERIFICATION AND DATA COLLECTION - Following the aerial survey, individuals of the Forest Pest Management staff verified the area of each stand containing tree mortality, classified the stands by damage stratum, and listed the stands in numerical order. The number of samples needed was calculated for the expected variance within strata. These variances were estimated from previous surveys. Stands were then selected within stratum with probability of selection being proportional to stand size (PPS).

A sample consisted of live and dead spruce and fir trees located at five prism points (10 BAF)[4/] equally spaced along a predetermined line through a selected stand. The minimum tree size was 5 inches DBH. Host trees,

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[4/] Basal area factor.

obviously killed by agents other than spruce budworm, were not sampled. Trees with brown streaking in the cambium layer and suspected of dying because of budworm attack were listed as dead. Trees determined to be dead before 1977 were not tallied. Each sample tree had to contain at least one 8-foot bolt with a minimum small end diameter of 4 inches dib[5]. Data recorded for each stand were: tree species, trees live or dead, and number of bolts. Volume per acre was calculated for each sample stand, by dead and live categories, using Ashley's (1980) formula:

$$\text{cords/acre} = \frac{\text{number of countable trees + number of bolts}}{\text{2 times (number of [sample] points)}}$$

Stratum means, number of samples in a stratum, and stratum areas were pooled to calculate the mean volume per acre of dead and live host trees.

SURVEY TECHNIQUE 3 - AERIAL SKETCH MAPPING, LARGE SCALE AERIAL PHOTOGRAPHY AND GROUND SAMPLING

This sampling technique (White et al. 1983) utilized a multistage design based on a combination of forest stand type maps, aerial sketch mapping, large scale aerial photography, and ground sampling to estimate tree and volume loss for one or several classes of tree mortality.

FOREST STAND STRATIFICATION/AERIAL SKETCH MAPPING PROCEDURES - The stratification of forest stands was accomplished by using forest stand maps showing species strata (white spruce, black spruce, balsam fir, and mixed conifer). Stands were further stratified into three mortality strata: few, moderate, and severe, using the aerial sketch mapping procedures outlined in Technique 2.

A 10 percent random sampling of all (414) stratified stands within the two strata (species and mortality) was used to select 40 stands for photo sampling.

AERIAL PHOTO ACQUISITION - The aerial photo mission was flown on August 2-7, 1983, using a Forest Service Beechcraft Queen Air photo aircraft. The airplane was equipped with a Zeiss mapping camera system consisting of a RMK 21/23 9-inch aerial format camera with a 210 mm (8-1/4 inch) focal length lens, an intervalometer system to control proper interval/overlap between photos, and an NT-1 navigation telescope for visual navigation (Myhre 1984).

All 40 sample stands were photographed with color film (Kodak Ektachrome EF, Type SO-397) at a scale of 1:6,000. Seven of the stands were rephotographed with color infrared film (Kodak Aerochrome Infrared-Type 2443) for comparison. To acquire 1:6,000 scale photography, all flight lines were flown at 4,100 feet above mean ground elevation. Photo strips were flown across each stand in cardinal directions, depending on the direction of the longest axis of the stand. Three to six exposures (photos) were taken over each stand to ensure stereo coverage, again depending on the size of the stand.

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[5] Diameter inside bark.

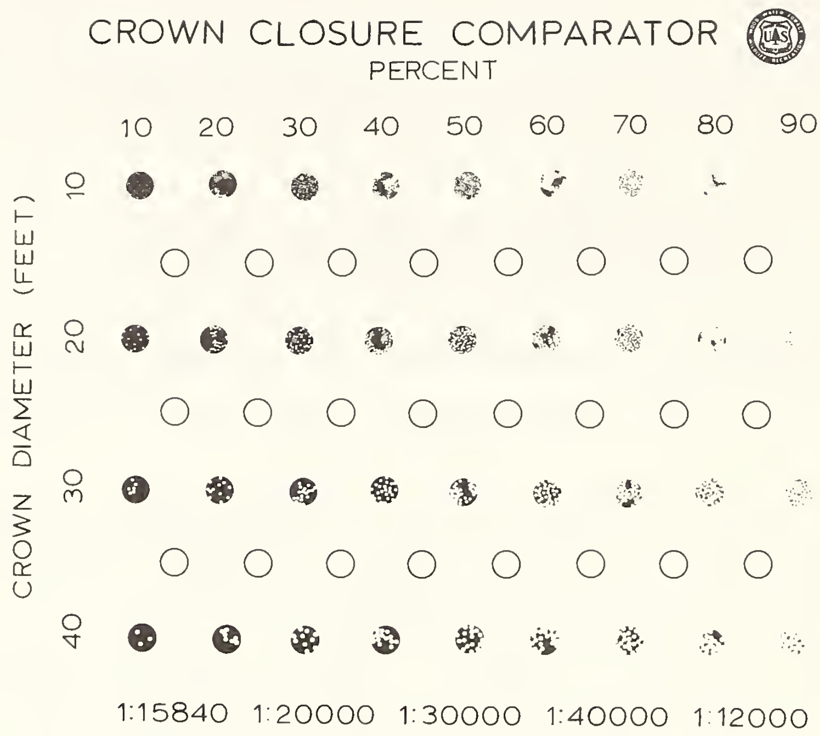

Figure 1 - Crown closure comparator reduced for illustrative purposes (Aldrich and Norick 1969).

Visual navigation over the Nicolet National Forest and from one stand to another was performed with the aid of a 0.5 inch/mile map annotated with all sample stand locations. Photo navigation over each stand was performed with the aid of stand maps and black and white aerial photos taken earlier at a scale of 1:15,840.

PHOTO INTERPRETATION - Preparation - Once the film was processed, it was cut into individual frames (photos) and placed in protective transparent sleeves. Photo coverage of each stand was placed in a separate envelope and labeled by ranger district, compartment number, and stand number for ease of storage and retrieval. Index maps were prepared to show the location of all photo sample coverage by plotting the centers of each photo on the stand maps.

Stand boundaries were inked on the transparent sleeves by visual transfer from the stand map to the aerial photo. A Bausch and Lomb Zoom Transfer Scope was used to perform this task.

Photo Interpretation Aids - Photo interpretation (PI) aids consisted of a transparent sampling grid overlay, parallax wedge, and a crown closure/crown diameter estimator (fig. 1) photographically reproduced for the 1:6,000 scale photography.

The grid overlay contained 100 cells (10x10 matrix) where each cell represented a 1-acre subplot on 1:6,000 scale photography. Prior to the actual PI, a grid was randomly placed over each stand and secured to the transparent sleeve with tape. Forty computer generated random numbers tables were prepared for the purpose of selecting 1-acre subplot samples. In order to be accepted, a cell needed to fall completely within the boundary of the stand. Three 1-acre cells were selected for stands of 100 acres or less; and for stands of over 100 acres in size, one additional cell was selected for each 100 acres over the first 100.

Estimates of average tree height for each stand were measured stereoscopically with a parallax bar (Avery 1962). The crown closure/crown diameter estimator illustrated various percentages of crown closures (horizontal) and crown diameters (vertical). The photo interpreter utilized this aid to estimate crown diameter and closure. The estimates of stand crown diameter and closure and average tree height were used as an index into aerial photo stand volume tables (Meyer 1961). With these values obtained from the aerial photos, it was possible to estimate stand volume, thus eliminating the need for on-the-ground data collection.

Data Acquisition - Photo interpreters used Old Delft scanning stereoscopes on light tables to obtain the following types of information for each 1-acre subplot sample:

- Total dead trees.
- Total live balsam fir trees.
- Total live spruce trees.
- Sum of live balsam fir and spruce trees.
- Average crown diameter.
- Average crown closure.
- Average stand height.

GROUND VERIFICATION AND DATA COLLECTION - Two 1-acre subplots were selected through PPS for ground verification from each of ten (four with tree mortality classified as "few", four classified as "moderate", and two classified as "severe") of the forty stands photographed. The measure of size in PPS in this technique refers to number of dead trees, not acres.

The total number of dead trees in the stand, as estimated from the aerial photos, was used as a stand selection criteria. The total number of dead trees in a 1-acre plot, again as measured on the photo, was used as the selection criteria for sample plots within a stand.

Photo transparencies and Nicolet National Forest compartment maps were used to locate selected stands. Subplot boundaries were located by utilizing photo transparencies viewed with the aid of a field stereo viewer (Klein and Lory 1981), using transmitted sunlight as the light source.

Ground data were obtained by first delineating subplot boundaries with string or flagging. If faders were numerous within a subplot, it was further subdivided into 1-chain-wide-strips to facilitate examination. Next, the number of dead (down and standing) and dying trees 5 inches dbh and larger were recorded by 1-inch diameter classes. The heights of three spruce and balsam fir trees were obtained for each diameter class for future volume estimates. Volume estimates were obtained by constructing a local volume function, as explained in technique 1, (Mog and Witter 1979, after Gevorkiantz and Olsen, 1955).

Specific formulae used for statistical analysis are explained in the appendix. The analysis consisted of volume loss estimates for each strata and its associated standard error. Both estimates are expressed in cords per acre. An overall volume loss and standard error was then obtained for spruce-fir type on the Nicolet National Forest.

RESULTS

The three techniques: (1) ground sampling; (2) aerial sketch mapping and ground sampling; and (3) aerial sketch mapping, aerial photography and ground sampling are compared relative to respective volume loss estimates with related precision and project costs.

VOLUME LOSS

Ground data was used in lieu of aerial stand volume tables to calculate volume loss for technique 3 because: (1) photo crown closure percent was often less that 15 percent; and (2) tree height was usually less than 45 feet. This resulted in a standard error of the estimate of $\pm$ 44 percent of average plot volume.

Volume loss estimates due to budworm-caused tree mortality are presented as cords/acre with the related standard error and relative standard error of that estimate (table 1).

Table 1 - Average estimated dead volume per acre, standard error, and precision of each technique used on the Nicolet National Forest, Wisconsin, 1983.

	Species	Dead Volume (Cords/Acre)	SE (Cords/Acre)	Relative Standard Error (Percent)
Technique 1	Fir	1.78	±0.40	23
	Spruce	0.45	±0.16	36
Technique 2	Spruce & Fir	2.77	±0.44	16
Technique 3	Spruce & Fir	2.03	±0.37	18

For technique 1, the total dead volume on the Nicolet National Forest was calculated by multiplying the total spruce and balsam fir acreage on the Forest by the average estimated dead volume. With techniques 2 and 3, the total dead volume was obtained by multiplying only spruce and fir acreage where mortality was present (17,234 acres) (table 2).

Table 2 - Estimated total dead volume lost on the Nicolet National Forest, Wisconsin, according to each tecnhique, 1983.

	Species	Acreage[1/]	Total dead volume (cords)	SE
Technique 1	Fir	18,400	32,752	±7,360
	Spruce	9,518	4,283	±1,523
Technique 2	Spruce & Fir	17,234	47,738	±7,582
Technique 3	Spruce & Fir	17,234	34,985	±6,377

[1/] Acreage for Technique 1 is based on total spruce and fir acreage on the Nicolet National Forest. Acreage totals for Techniques 2 and 3 are based on stratified sampling of the spruce and fir type, and recording only those acres with spruce and fir mortality.

PROJECT COSTS

Total project costs expended on each of the three techniques are presented in table 3.

Table 3 - Representative project costs for each technique used in the 1983 spruce budworm loss assessment survey on the Nicolet National Forest

Item	Technique 1	Technique 2	Technique 3
Wages[1/]	$4150 (692 hr)	$3120 (520 hr)	$1500 (250 hr)
Travel	3350	1584	1850
Vehicle mileage[2/]	1087 (4350 mi)	537 (2150 mi)	481 (1925 mi)
Materials	150	150	100
Data analysis	400	300	600
Other direct costs:			
Aerial sketch mapping	--	1900	1900
Photo acquisition[3/]	--	--	6550
Photo interpretation	--	--	1700
Total project costs	9137	7591	14681

[1/]Labor calculated at $6.00 per hour.
[2/]Mileage calculated at $0.25/mile.
[3/]Covers aircraft cost, film, and processing, crew salary, and travel expenses. Of this line item cost, $3,000 was for aircraft ferry time.

Wages represented the largest cost percentage for techniques 1 and 2, comprising 45 and 42 percent of the total project costs. For Technique 3, the cost of photographic acquisition represented the largest monetary expenditure (49 percent). The cost of ferrying the photo aircraft to the survey area was a large portion (46 percent) of the photo acquisition cost.

A cost per acre figure (table 4) was obtained by dividing the total project cost for each technqiue by the total host type acreage on the Forest. Technique 2, at a cost of $0.27 per acre, was 18 percent ($0.06) less expensive than technique 1, and 49 percent ($0.26) less expensive than technique 3.

If aircraft ferry expenses ($3,000) were not included as a direct cost item under photo acquisition for Technique 3, the per acre cost could be reduced from $0.53 to $0.41, thus making Technique 2 thirty-four percent less expensive.

Table 4 - Per acre cost by technique to obtain spruce-fir mortality data.

	Total Cost ($)	Cost/Acre ($)
Technique 1	9,137	0.33
Technique 2	7,682	0.27
Technique 3	14,681	0.53

The method, number, and size of ground sampling units (plots) for each technique varied greatly (table 5). Although technique 3 required the fewest number of ground plots (20), the relative size of each plot was significantly larger than those used for the other two techniques. The number of plots taken for techniques 1 and 2 were 93 and 140 respectively. Technique 2 required the greatest number of plots, however, the prism point method was more efficient than the fixed-radius plots employed in techniques 1 and 3.

Table 5 - Description of samples required by each technique.

Description	Technique 1	Technique 2	Technique 3
No. of spruce-fir stands sampled	31	28	10
Sample method	Fixed-radius	Prism	Fixed-size[1/]
Sample size	0.20 & 0.05 acre	10 BAF	1 acre
No. of sample points/stand	3 of each size	5	2

1/ Rectangular plots.

DISCUSSION

The following discussion addresses three major topics: comparison of the survey estimates, comparison of the survey costs, and limitations of each technique. These discussions provide the basis for an objective assessment of the three techniques in estimating timber loss due to eastern spruce budworm

in the spruce-fir forest type. Three additional concerns are also addressed: (1) the applicability of aerial photo stand volume tables; (2) ascertaining appropriate aerial film type; and (3) utility, if any, for each technique in estimating residual stand volume and basal area.

COMPARISON OF ESTIMATES

Forest Pest Management personnel have established a relative standard error of 20 percent of the mean as that level of survey precision desirable for collecting pest-induced tree mortality and growth loss information (Ciesla and Yasinski 1980). This level should provide land managers with adequate pest-caused loss information upon which to base management decisions.

The ground sampling technique 1, developed by Mog et al. (1982) resulted in relative sampling errors of 23 and 36 for fir and spruce respectively. The relative sampling error for the fir type was only 3 percent above the established level; a small investment in additional sampling would probably bring this error under 20 percent. It may prove more difficult to reduce the spruce estimate from 36 to 20 percent.

The relative sampling errors for techniques 2 and 3 were 16 and 18 percent respectively - well within the stated objective of 20 percent. In techniques 2 and 3, classifying the stands into mortality strata reduced the number of ground plots needed to assess overall volume loss.

If land managers would prefer to utilize the volume loss data for a particular stratum rather than use the overall estimate, they would have to accept higher standard errors associated with each stratum or increase the number of stands sampled. For an agreed upon variance, the number of stands sampled per stratum may be reduced by using better classification during aerial sketch mapping and by increasing the number of ground plots per stand.

COMPARISON OF COSTS

Technique 2 is the least expensive technique to implement. However, as pointed out earlier, if ferry expenses for the photo aircraft could be significantly reduced, the cost of Technique 3 would become more cost effectivce. Aircraft ferry expenses can be greatly reduced by coordinating the scheduling of a survey mission with other photo missions, thereby providing a cost sharing of this expensive direct cost item. Before selecting one technique over another, however, project costs should be tempered with related aspects such as statistical efficacy and precision, as well as technique limitations.

LIMITATIONS OF EACH TECHNIQUE

Technique 1 does not stratify tree mortality on a stand-by-stand basis. Without this type of information, a resource manager would be unable to establish individual stand prescriptions.

Technique 1 requires information from a large number of ground plots to assess overall volume loss. Such data acquisition is labor intensive, and thus, costly. Expenditure of human and dollar resources seems inappropriate, especially since tree mortality is not stratified on a stand by stand basis.

Technique 2, which employs sketch mapping to stratify mortality without prior knowledge of stand locations, may include areas of nonhost type. This is a very real problem in the Lake States where balsam fir stands are often interspersed with other tree species.

Both techniques 2 and 3 employ aircraft and are therefore, weather dependent; this can often slow data acquisition. Technique 3 requires two separate aerial surveys at different time periods, thus increasing the chances of weather related delays.

Techniques 1 and 2 do not provide permanent photo records which can be used to compare future changes.

Estimating volume loss from aerial photos and aerial photo stand volume tables proved to be quite unreliable for two reasons. First, the aerial photo stand volume tables had an inherently high standard error of the estimate ($\pm$44 percent). Second, a large number of trees (60 percent) were not observed on the aerial photos. These omission errors were due to the inability of the interpreter to distinguish smaller diameter trees ($\leq$5 inches dbh) found in the understory. In addition, many of the dead trees had the tops broken out, making observation from aerial photos nearly impossible.

For future surveys, the use of color infrared film may prove to be superior for estimating tree mortality, especially where small diameter trees are prevalent as is typical of the spruce-fir type of the Lake States region. Use of color infrared film may enable the interpreter to more easily distinguish and count dead trees. Color infrared is superior to normal color film due to its ability to penetrate and reduce the effects of haze. In addition, the superior color contrast of infrared film increases a photo interpreter's ability to separate conifers from hardwoods and distinguish between live and dead conifers (Klein 1982).

Basal areas of live and dead spruce-fir type can be obtained using data collected from any of the three techniques. However, because of sampling designs and methods of analysis, residual volume can only be obtained from techniques 1 and 2, and estimates of live and dead trees per acre by using Technique 1 or 3.

CONCLUSIONS

Each survey method was capable of estimating spruce-fir volume losses caused by spruce budworm, within specified error limits, on the Nicolet National Forest. The two procedures using aerial classification can be used

to determine the location of tree mortality. The precision for techniques 2 and 3, where stands were stratified in mortality classes, met the survey objective with a relative sampling error within 20 percent of the mean.

Comparing all techniques for cost and precision, technique 2 gave the best estimate of volume lost at the lowest cost per acre. Large scale photography as required for technique 3, was an effective method for estimating volume loss as demonstrated by the precision obtained with significantly less information collected in the field; however, the cost was higher. Use of small format (35 or 70 mm) photography may make technique 3 more cost effective.

ACKNOWLEDGMENTS

We thank the following individuals for their important contributions in this study:

Bob Ford, USDA Forest Service, Forest Pest Management, St. Paul Field Office, for technical advice and assistance relating to methods described in technique 2.

Tom Hakala and Tim Loose, USDA Forest Service, Forest Pest Management, St. Paul Field Office, for photo interpretation and ground sampling.

Bill Jackson and Scott Lowe, USDA Forest Service, Forest Pest Management, St. Paul Field Office, for ground sampling.

Harry Hubbard, USDA Forest Service, NEFES, Hamden, Connecticut, for photo interpretation.

Ann Lynch and John Witter, University of Michigan, for helpful discussions and comments relating to methods described in technique 1.

Ron Bell, USDA Forest Service, Region 2, Denver, Colorado; and Ken Latham, Elmo Aero, Lake Elmo, Minnesota, Pilots.

Jim Hanson and Peter Rush, USDA Forest Service, Forest Pest Management, St. Paul Field Office; Bill Ciesla, USDA Forest Service, Forest Pest Management Methods Application Group, Fort Collins, Colorado; and Dick Cutler, USDA Forest Service, Nicolet National Forest, for their constructive review of this manuscript.

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APPENDIX

Formulae used for statistical analysis with survey technique 3

A four-phase sampling scheme was employed in survey technique 3. Stands were placed into one of three mortality strata using aerial sketch mapping. Within each of these strata, stands were selected at random for photo sampling. From these stands a sub-sample of stands was selected within each strata for ground checking. This sub-sample of stands was selected using probability proportional to size (PPS). The total number of dead trees in the stand, as seen on the aerial photo, was used as the measure of size. Within a stand selected for ground checking, two one-acre cells were selected as the plots to be visited. These plots were selected from other 1-acre cells on the photo using PPS. The number of dead trees seen on the plot, using the aerial photos, was the measure of size in this last selection.

The estimate of the volume of mortality, V, and the variance, S^2, of that estimate can be calculated as follows:

$$V = (A/B)*(1/n)*\sum_{i=1}^{n}(Vi/Pi),$$

and

$$S^2 = (A/B)^2*1/(n*[n-1])*\sum_{i=1}^{n}(Vi/Pi-[1/n]*\sum_{i=1}^{n}[Vi/Pi])^2,$$

where, A is the area of the strata,
B is the area of the strata selected to be photographed,
n is the number of stands selected to be ground checked,
Pi is the probability of selecting the ith stand among the photographed stands in the strata,
Vi is the volume of tree mortality determined in the ground checking.

The selection probability for a stand, Pi, is calculated as follows:

$$Pi = ai*\sum_{k=1}^{3}tik/(\sum_{i=1}^{n}ai*\sum_{k=1}^{3}tik),$$

where, ai is the area of the ith stand,
tik is the number of dead trees on the kth plot of the ith stand, as seen on the photo.

The volume of tree mortality, Vi, in a stand is calculated as follows:

$$Vi = (ai/3)*(1/2)*\sum_{k=1}^{2}(vik/pik),$$

where, vik is the volume of tree mortality on the kth plot in the ith stand,
pik is the probability of selecting the kth plot in the ith stand.

The last term, pik, is calculated as:

$$pik = tik/\sum_{j=1}^{3} tij.$$

The variance is based on a two-stage PPS sampling (Langley, Cochran). This adjusted formula assumes a sufficiently large initial random sample.

U.S. GOVERNMENT PRINTING OFFICE: 1985—577-869/25134 REGION NO. 8